

# GaAs(Si) as a Low-Background Scintillator for Direct Detection of Dark Matter

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# Outline

- History and Objectives
- LBNL scintillator research facility
- GaAs crystal samples
- Preliminary measurements
  - X-ray excited emission spectrum
  - Pulsed X-ray time response
  - Optically excited emission spectrum
- Conclusions
- Path forward

# History and Objectives

Rouven Essig, Andrea Massari, Adrián Soto, and Tien-Tien Yu, Stony Brook University, NY proposed that

A low band-gap scintillator and cryogenic photodetectors could detect photons from electrons excited by DM interactions

- Improved reach for MeV DM

- Single photon sensitivity and low backgrounds

- Complementary to other approaches

- => Paper in review (NaI, CsI, GaAs)

Matt Pyle, UC Berkeley

- Importance of considering afterglow

LBNL Scintillator research group

- Decades of scintillator research, including cryogenic semiconductor scintillators

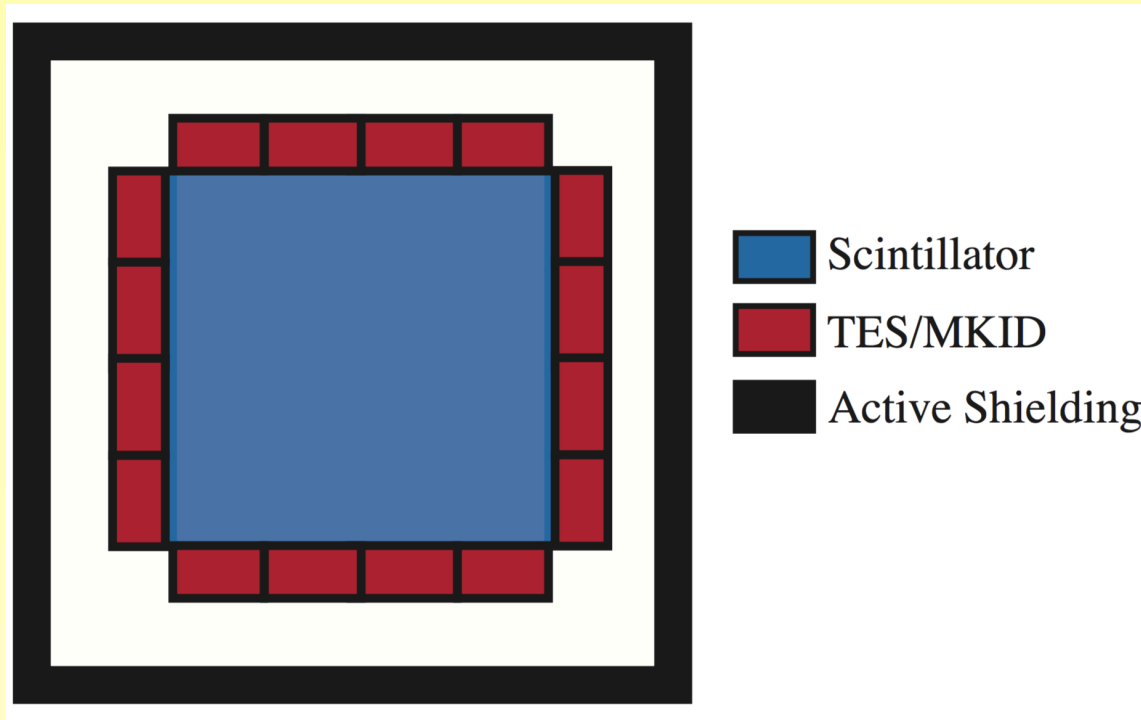
- GaAs measurements

# Why GaAs for Detecting Electrons Excited by DM?

- Why scintillation rather than charge collection?
    - Afterglow decays, dark current does not
    - No spontaneous electron excitation at 0K and zero E field  
excitation energy = 4000 kT at 4K
    - Can detect individual photons with very low background
  - Why NaI or CsI?
    - Lower band gap (1.5 vs. 6 eV)  
lower DM mass reach  
4x more photons for background rejection and spectroscopy
    - not hygroscopic
  - Why not another semiconductor?
    - For >1 photon detection GaAs is direct-gap and faster than indirect gap Si and Ge
    - Commercially grown as large single crystals
    - GaAs(Si) cryogenic QE 60% reported\*
- \* Cusano, Solid State Communications, 2:353-358, 1964



# Scintillator, Photodetectors and Active Shielding



- 10 x 10 x 10 cm (5 kg) GaAs crystal
- Transition edge sensors or  $\mu$ wave kinetic inductance detectors
- BGO scintillator active shield

# **LBNL Scintillator Research Group**

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**Stephen  
Derenzo**



**Edith  
Bourret-  
Courchesne**



**Gregory  
Bizarri**

Post-docs, technical staff

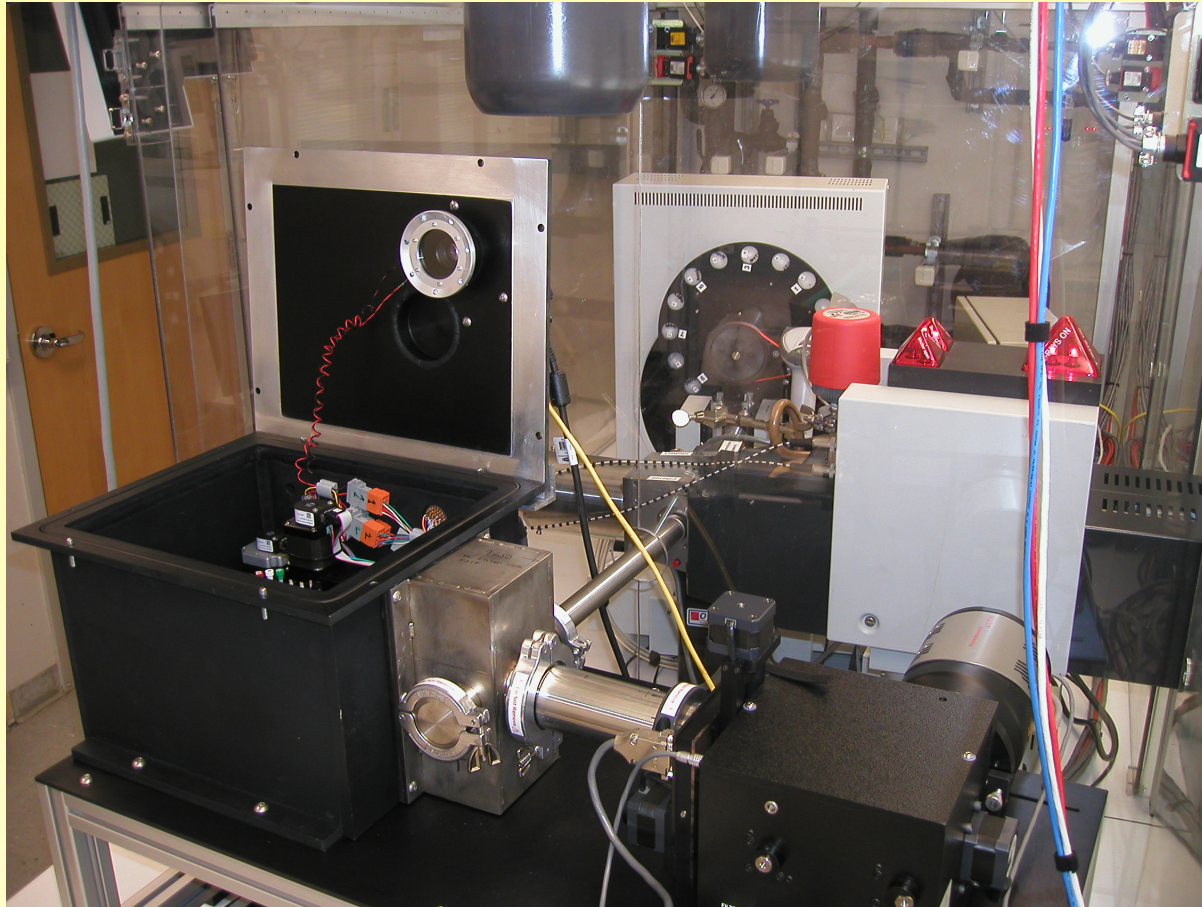
Open-access database of scintillation properties

<http://scintillator.lbl.gov>



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# Optical and X-Ray Excited Luminescence Spectrometer

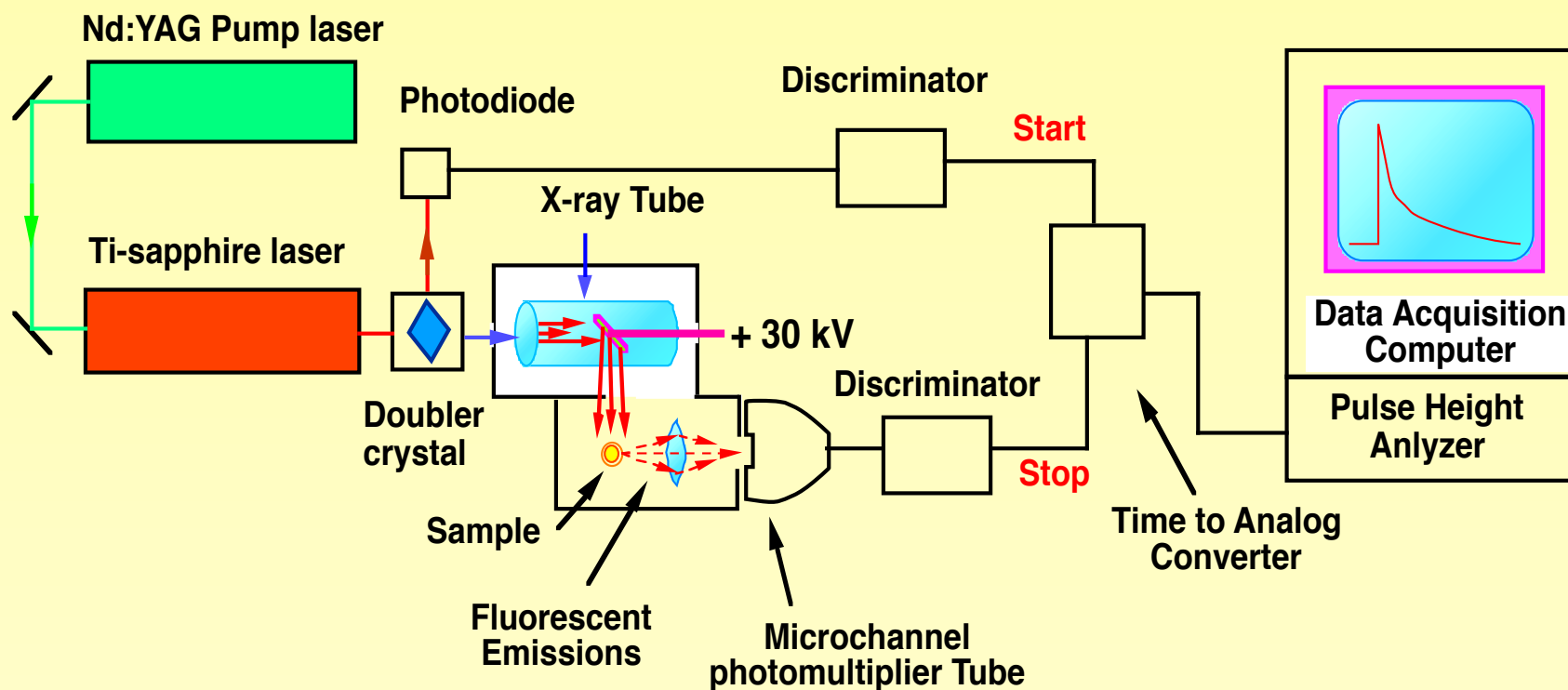


Optical  
monochromator  
Rotating anode  
X-ray machine  
(40 kV, 100 mA)  
Spectrometer  
with order-  
sorting filters,  
two gratings, and  
CCD readout  
(250-970 nm)



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# Pulsed X-Ray Time Response Measurements



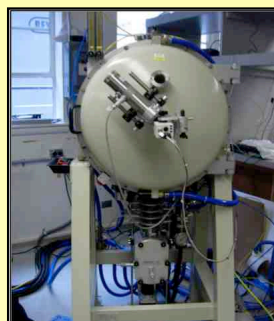
Also: laser diodes for pulsed optical excitation



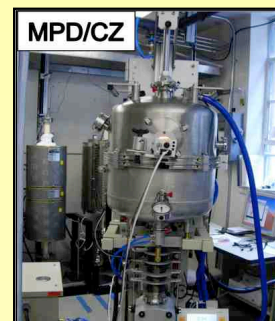
# LBNL Crystal Growth Facility (Bldg 64)

Unique US facility to screen, optimize, and produce detector materials in single crystal form

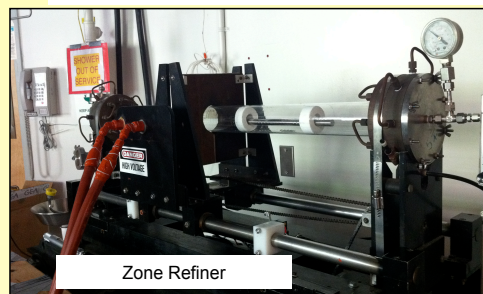
- 8 Bridgman/Stockbarger furnaces
- 3 Mirror furnaces
- 2 Czochralski furnaces
- 2 Micro-pull down furnaces
- 2 Zone-refiners
- Multiple box and tube/rocking furnaces
- Drying ovens



Induction heating / Controlled atmosphere

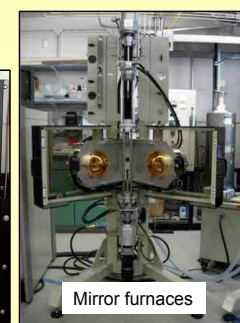
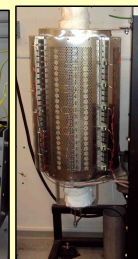


Czochralski furnace/medium pressure

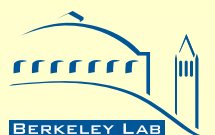
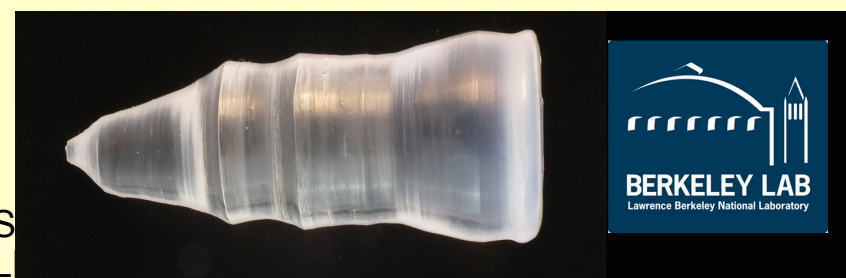
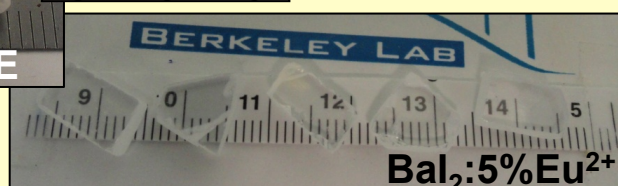
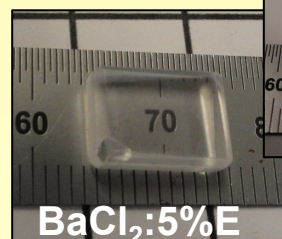
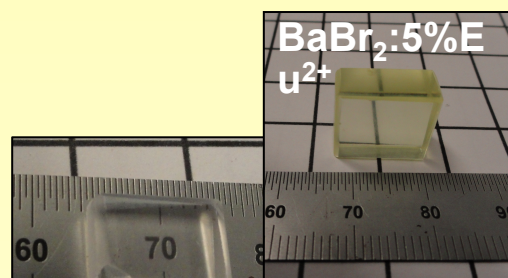


Zone Refiner

Bridgman furnaces



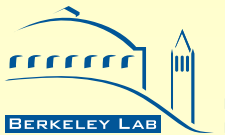
Mirror furnaces



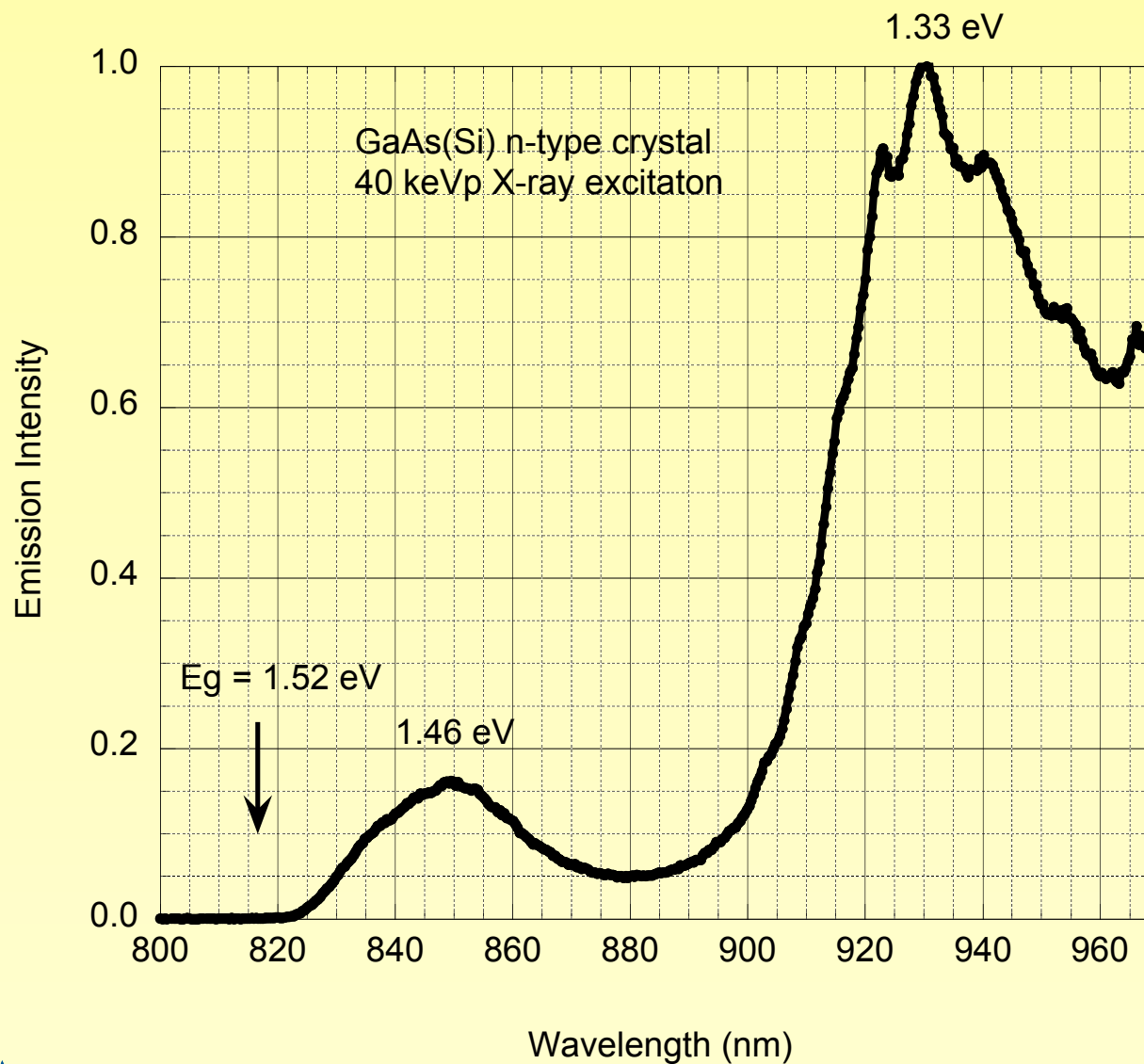
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# GaAs Crystal Samples

- GaAs properties
  - Density 5.32 gm/cm<sup>3</sup>
  - Band gap 1.52 eV (direct) near 0K
  - Refractive index 3.3 (infra-red)
- GaAs(As) (semi-insulating)
  - Excess As atoms on Ga sites (antisite defects)
  - Fermi level pinned near the center of the band gap
  - High electrical resistivity
- GaAs(Si) n-type
  - Si<sup>4+</sup> atoms on Ga<sup>3+</sup> sites (donor defects)
  - Si<sup>4+</sup> ions are charge compensated at room temperature with conduction band electrons
  - Low electrical resistivity at room temperature
  - Donor-bound exciton emission at cryogenic temperatures



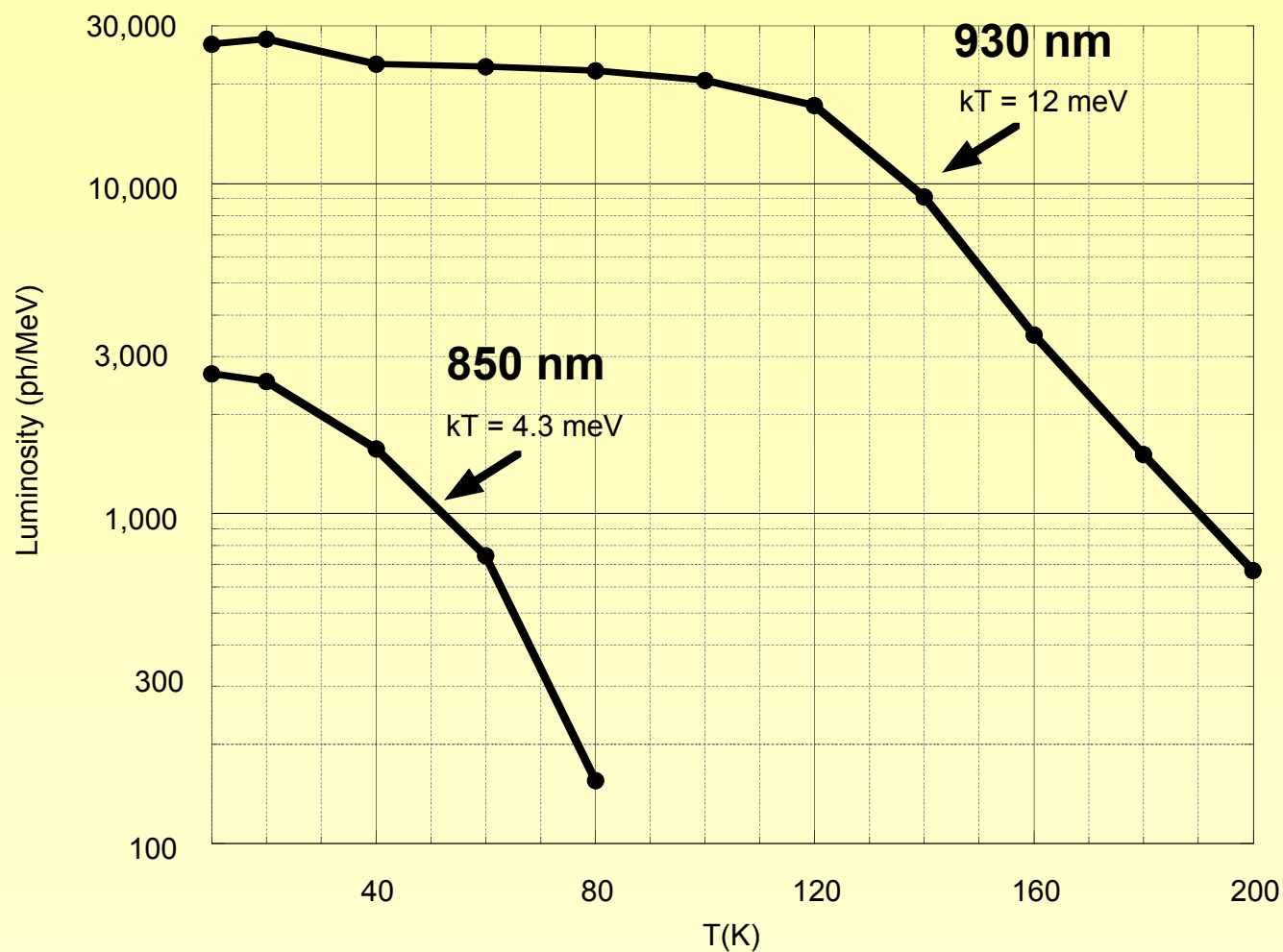
# Emission spectrum at 10K



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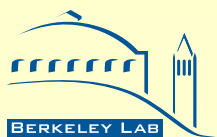
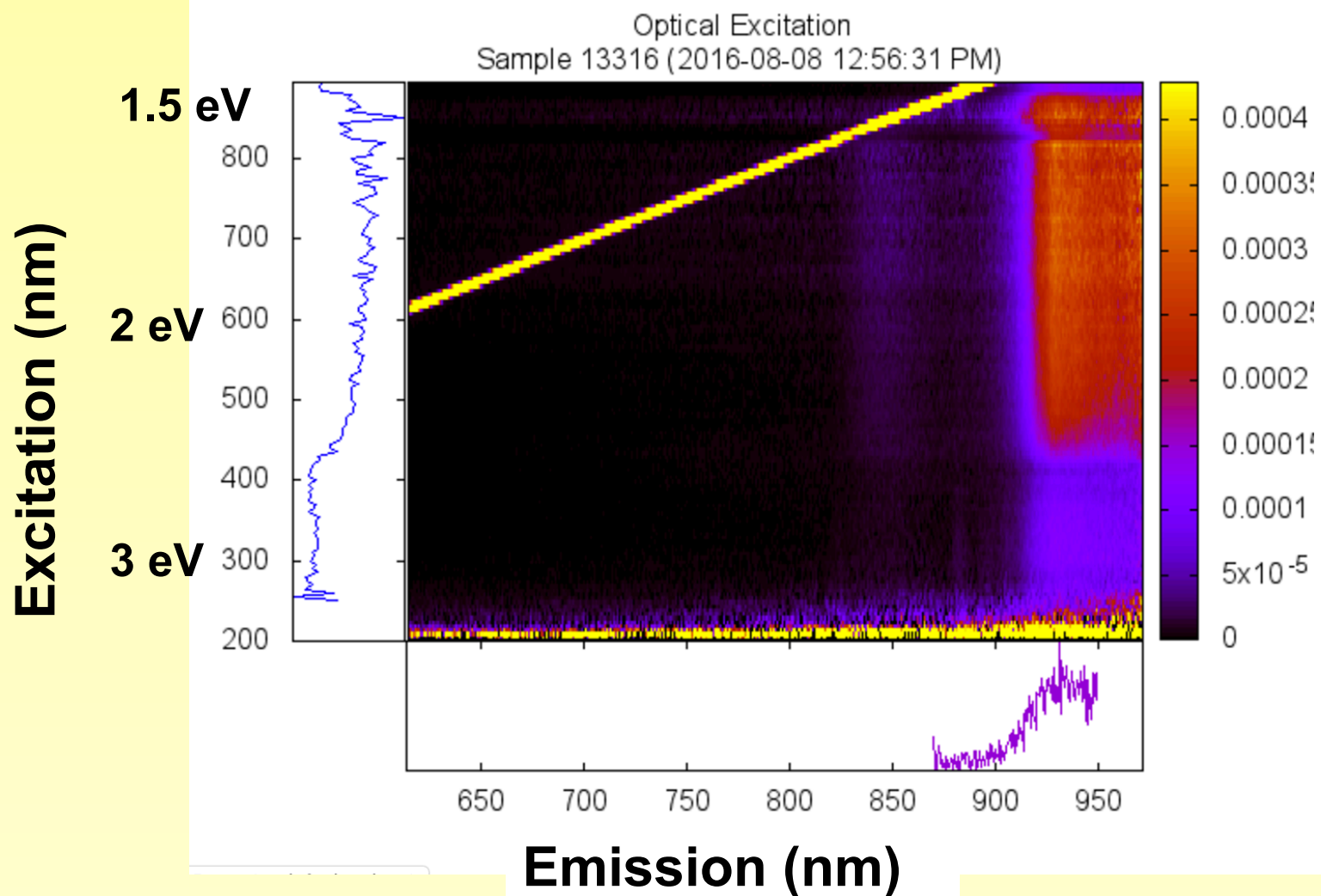
# GaAs(Si) luminosity vs. temperature

40 keVp X-ray excitation

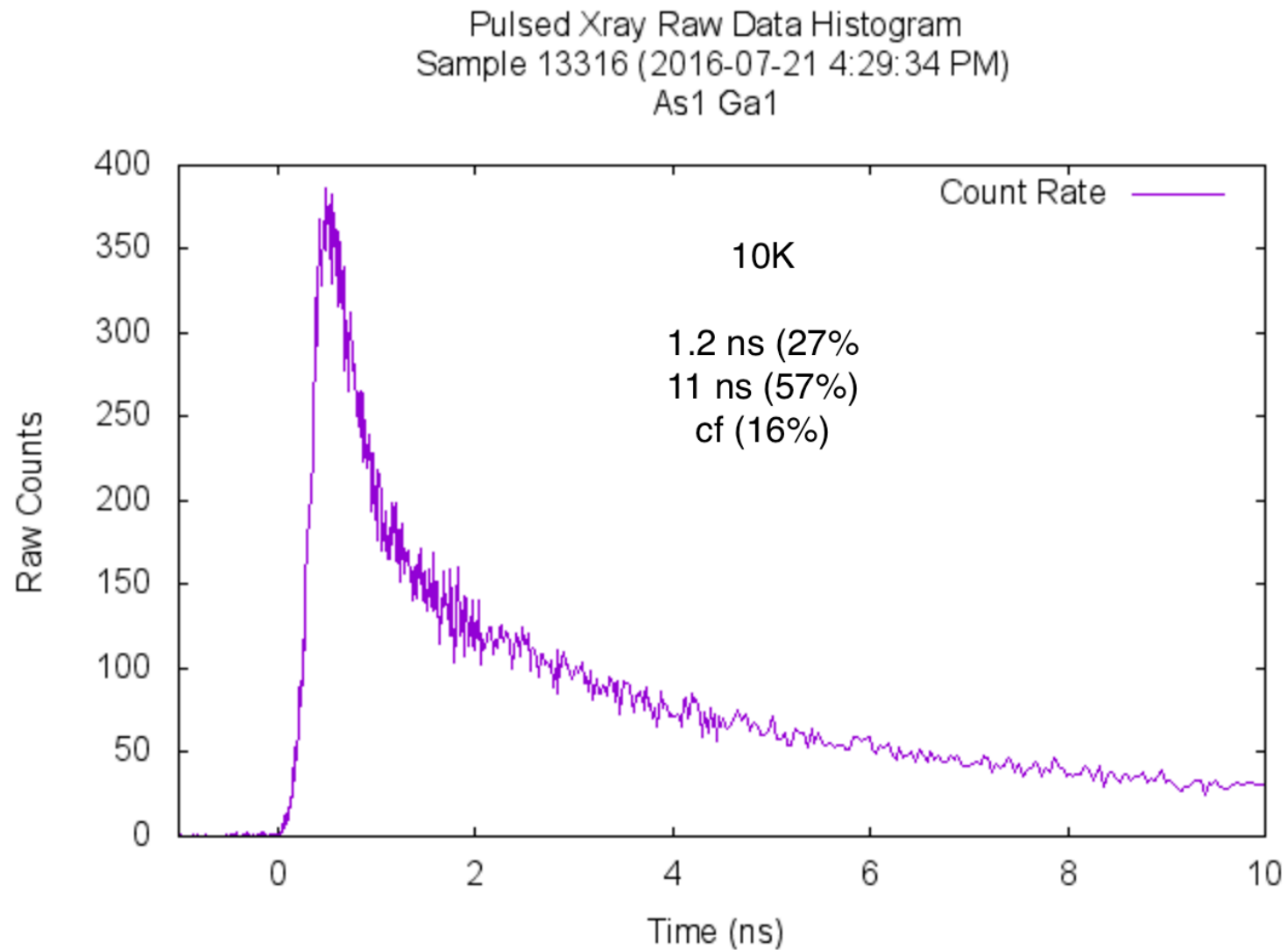




# Optical excitation/emission spectrum 10K



# GaAs (Si) Decay Spectrum



## Effect of Si doping on GaAs cryogenic data

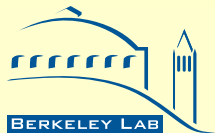
|  | GaAs(semi-insulating) | GaAs(Si)                    |
|--|-----------------------|-----------------------------|
| X-ray excited luminosity (photons/MeV) | <0.05                 | 30,000*                     |
| X-ray excited emission                 | Not detected          | 850 nm (9%)<br>942 nm (91%) |
| Optically excited quantum efficiency   |                       | 60%**                       |

\* >970 nm excluded

\*\* Cusano, Solid State Communications, 2:353-358, 1964

Scintillation luminosity from separated e-h

Optical excitation QE from close e-h



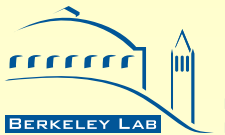
## Conclusions

- Silicon doping has a profound effect on the luminescence of GaAs ( $>500$  x undoped)
- X-ray luminosity 30,000 photons/Mev from 10K to 120K
- QE 60% from Cusano 1964
- There are two luminescent centers
  - 850 nm (0.06 eV from band edge)  
thermal quenching  $kT \sim 4.3$  meV
  - 930 nm (0.19 eV from band edge)  
thermal quenching  $kT \sim 12$  eV
- 90% of the light is in the 930 nm component

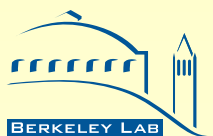


# Path Forward

- Initial components
  - Commercial boule GaAs(Si)
  - Cryogenic photodetectors (TES, APD)
- Emission tests
  - Emission intensity and spectrum - optical and X-ray excitation
  - Time response using pulsed X-rays
  - Gamma ray Compton spectrum
  - Afterglow
  - Cosmic rays
- Scale-up measurements
  - 1 kg crystal in 4K cryostat
  - TES photodetectors on 6 sides
  - Deep mine
  - 1 vs. 2 photon detection
  - Active shielding
  - Hollow crystal



# Thank You for Your Attention



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